# 2. CHARACTERISATION OF CRYSTALLINE BASEMENT AQUIFERS

## 2.1. Conceptual framework

Crystalline basement rocks (bedrock) are composed of hard, crystalline or re-crystallised rocks of igneous or metamorphic origin, such as granites, basalts, metaquartzites or gneisses with negligible primary porosity and permeability (Clark, 1985; Gustafson and Krásný, 1994). Crystalline bedrock is exposed (outcrops) in numerous locations throughout South Africa and covers approximately 15% of the total land area. However, almost the whole country is underlain by crystalline bedrock, albeit in places under a thick cover of more recent geological formations. They can be divided into three main suites in South Africa.

I. Ancient rocks of the Archaean cratonic nuclei (i.e. Kaapvaal craton), including granites, gneisses and greenstones, such as the Halfway House Granite in Gauteng, South Africa.
II. Metamorphic rocks of the mobile belts, showing strong deformation and often of Proterozoic age, such as the gneisses of the Limpopo Mobile Belt (i.e. Beit Bridge Complex).
III. Anorogenic intrusions of various ages, such as the Bushveld Igneous Complex and Cape Granite Suite.

Potential composite aquifers are developed within the weathered overburden and fractured bedrock of these crystalline rocks, and are commonly referred to as basement-, hard rock-, bedrock- or weathered-fractured rock aquifers. In this study, the focus will be on the Archaean age crystalline lithologies.

### 2.1.1. Classical weathered-fractured rock concept

Although more detailed weathering profiles for crystalline rock can be found from recent literature (i.e. Dewandel et al., 2003), the classical (traditional) weathering-fracturing concept proposed in the 1980s and 1990s (i.e. Jones, 1985; Acworth, 1987; Chilton and Foster 1995) still applies to most crystalline basement terrains. The "classical" model of a basement aquifer refers to the following layers which have specific hydraulic properties (illustrated in Figure 2.1):

- An overlying regolith (unconsolidated material derived from prolonged in-situ decomposition of bedrock.), with a thickness from negligible to a couple of tens of meters.
    - Weathering is more rapid in tropical parts of Africa, whilst in arid areas or higher-lying areas where the rate of weathering is low in comparison with that of erosion, the regolith may be thin or absent.
    - The regolith usually has a high porosity and a low permeability (due to clay-rich material) (Acworth, 1987). When saturated, this layer constitutes the reservoir of the aquifer.
- The porosity of the weathered profile generally decreases with depth, along with clay content, until fresh rock is reached.

- This fractured-weathered layer is generally characterized by a fracture density that decreases with depth, and which can be related to cooling stresses in the magma, subsequent tectonic activity (Houston and Lewis, 1988) or litho-static decompression processes (Wright, 1992)
- The horizon of fracturing between the fresh rock and the regolith frequently has a higher permeability, depending on a number of factors including the nature of the fracturing and the presence of clay in the fractures.
- This layer mainly assumes the transmissive function in the aquifer and is pumped by most of the wells drilled in hard-rock areas (Maréchal et al., 2007).

- Fresh basement (un-weathered) is permeable only locally where deep tectonic fractures are present.
  - The structural features are extremely variable in nature (with regard to frequency, spatial extent, interconnectedness, etc.) within the relatively impervious crystalline rock mass (Gustafson and Krásný, 1994).

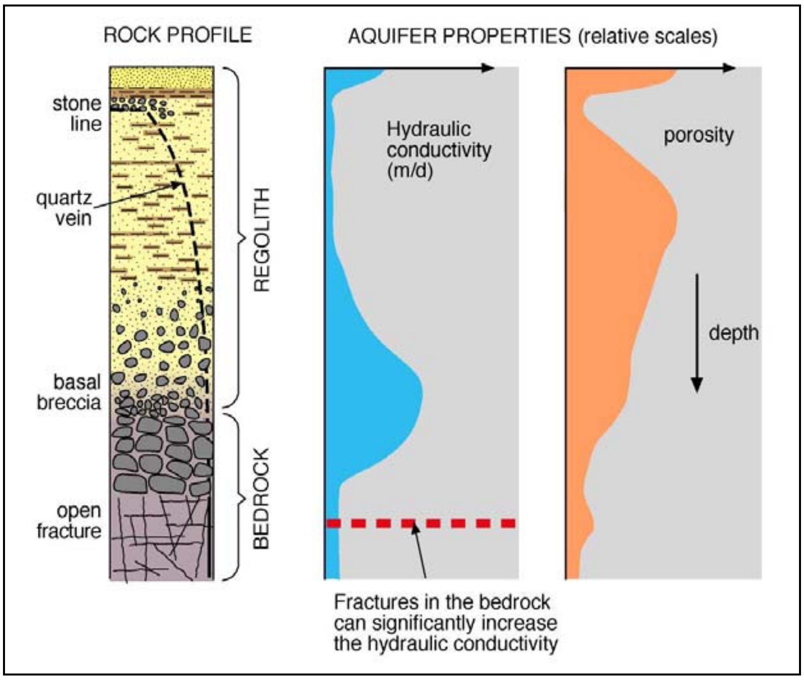


**Figure 2.1. Permeability and porosity in basement aquifers (Chilton and Foster, 1995).**

The main differences from one crystalline terrain to the next are in principal attributed to 1) the degree (thickness) of weathering and whether saturated or not, and 2) the extent of fracturing. However, these two complex components which largely influence the crystalline rocks potential as a groundwater supply depends on a number independent and interrelated factors on a regional and local scale. The common viewpoint (i.e. Wright and Burgess, 1992) of crystalline basement aquifers is that long-term borehole productivity relies on the presence of weathered material overlying the fractured rock or an alternative source of recharge such as a river or associated alluvium. Therefore, in more arid crystalline terrain with a lack of surface water resources and where a thinner weathered overburden is present, the interest of hydrogeologists in such aquifers is increased. In these cases focus is predominantly on the dominant fissure/fracture flow developed in the underlying fractured bedrock (i.e. Dutta et al., 2006; Galanos and Rokos, 2006; Neves and Morales, 2007; Titus et al., 2009).

### 2.1.2. General flow behaviour

Flow in hard-rock aquifers is inherently very complex and is governed by the hydraulic potential gradient and the hydraulic conductivities in the regolith and underlying fractured bedrock. A classical model for the recharge processes and flow systems in the crystalline basement regions of sub-Saharan Africa can be found in Wright (1992). Theoretical studies of two-dimensional groundwater flow in vertical sections by Tóth (1963) indicated that local, intermediate, and regional flow systems could be superimposed on one another within a groundwater basin. This is somewhat in contrast to the general flow behaviour of crystalline aquifers which suggest that groundwater flow is essentially shallow, focused in the weathered and fractured zone, generally limited to 50 metre below ground level. However, regional flow occurs within the major interconnected fracture systems, while the main groundwater flow systems are relatively localised to the zones between recharge on watersheds to discharge by run-off or evaporation at valley bottoms (Figure 2.2). Fractures exposed to the surface can create preferential flow paths which short circuit the path to the water table. Due to its higher porosity the regolith zone acts as a reservoir that slowly feeds water downward into fractures in the bedrock. Where good hydraulic interconnection is present between the basement rock and regolith, it is likely that excessive exploitation of the basement rock aquifer would induce vertical leakage from the regolith, thereby effectively utilizing the regolith's resource (Howard and Karandu, 1992). However, the recharge to the bedrock from the overlying regolith is generally difficult to estimate as it is governed by the hydraulic conditions at the regolith–bedrock interface. Consequently only a few published studies address the issue of recharge from soil (regolith) to bedrock. One such investigation conducted in central Sweden by Rodhe and Bockgård (2006) showed that a granitic bedrock aquifer was recharged by vertical flow from the overlying 10 m thick till soil, based on the assumption that the bedrock can be represented as a continuous porous aquifer.

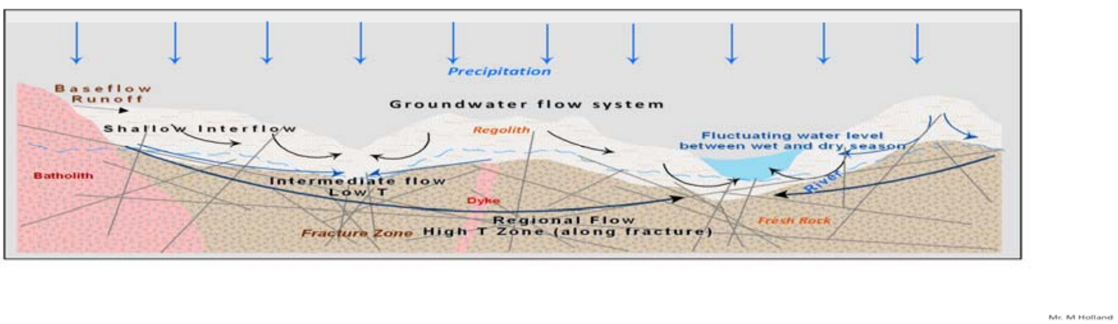


**Figure 2.2. Simplified flow system for crystalline basement terrain (Adapted from Tóth, 1963; Chilton and Foster, 1995).**

## 2.2. Groundwater recharge

Groundwater recharge can be defined as the portion of total rainfall falling into a drainage basin that ultimately reaches the water table in the phreatic zone of an aquifer (Freeze and Cherry, 1979). Recharge to crystalline basement rocks is a function of the mode of chemical weathering of the surface and the rate of fracturing (Lerner et al., 1990). Harte and Winter (1996) indicated that four factors influence bedrock recharge patterns: (1) relief of land and bedrock surface above groundwater discharge areas; (2) lateral trends in bulk-rock horizontal conductivity; (3) local topographic features; and (4) local drift stratigraphy. Recharge is directly related to rainfall, although this relationship is not linear as shown in Figure 2.3.

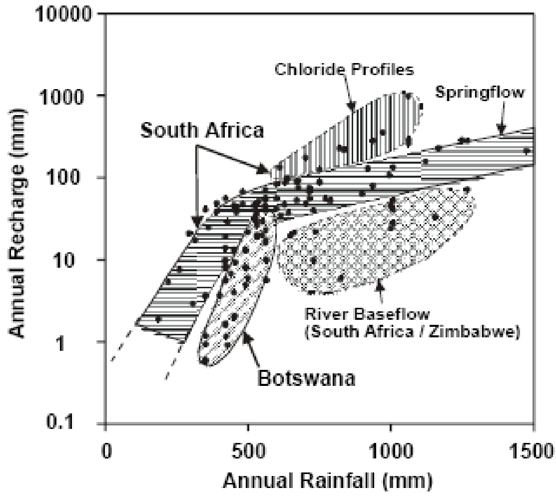


**Figure 2.3. Recharge estimates for southern Africa (Xu and Beekman, 2003; Adams et al., 2004).**

Across much of southern Africa potential evaporation is higher than average annual rainfall, and recharge is likely to be episodic and often via preferred pathways rather than uniformly distributed. Where mean annual rainfall is less than 400 mm, recharge from direct infiltration is likely to be small or negligible (Wright, 1992). Quantifying recharge is a common objective in many applications in groundwater hydrology in semi-arid areas such as the Limpopo Province and is especially relevant to discussions about groundwater sustainability. Methods of estimating recharge are subject to significant uncertainty in crystalline basement terrain, because of the heterogeneity and discontinuity of the aquifer and the resulting complexity of the groundwater flow system (Chilton and Foster, 1995). However, several of the conventional methods of recharge estimation can be used in semi-arid southern Arica if the underlying assumptions are taken into consideration (i.e. Xu and Beekman, 2003).

The Chloride Mass Balance (CMB) method has been suggested as the most reliable technique for determining recharge rates to fractured rock aquifers systems (Cook, 2003). However, the recharge rate determined from the CMB should be considered as a minimum rate because of the addition of other sources of chloride, which may occur, due to rock weathering (Banks et al., 2009). Therefore the CMB-method on its own might not give an accurate account of recharge estimations and should be used in conjunction with other recharge methods. Groundwater level fluctuations and rainfall correlation methods to estimate recharge have been applied in the

Namaqualand Basement aquifers (Adams et al., 2004). The analysis of water-level fluctuations can be useful for determining the magnitude of long-term changes in recharge caused, perhaps, by changes in climate or land use. Favourable aspects of the water fluctuation method include its simplicity and ease of use: it can be applied for any borehole that taps the water table, where an abundance of available water-level data exists (Healy and Cook, 2002).

## 2.3. Groundwater quality

Natural groundwater quality in most basement environments is generally good (Clark, 1985; Chilton and Foster, 1995), with low salinities and neutral to slightly acid pH values being common. However, salinities are elevated in areas of low recharge and/or prolonged residence times in the subsurface. Natural water quality in basement can occasionally be detrimental to human health through high levels of trace elements such as fluoride (Marais, 1999). Metals such as aluminium are also mobile in low pH groundwater. High iron concentrations associated with lateritic soils, whilst not harmful to human health, can stain appliances and clothes and make water unpalatable (Clark, 1985). Crystalline basement aquifers are very vulnerable to pollution of the groundwater, particularly where the regolith is thin, since groundwater movement through fractures is rapid and the fractured rock matrix provides little attenuation of contaminants. It is therefore necessary to test groundwater for natural quality, and groundwater development in a new area should always take water quality into account. Numerous village water supply boreholes in basement areas have been sited close to pit latrines, and microbial contamination has occurred, since both latrine and borehole penetrate to below the zone of lower permeability regolith. Poor water quality can be as great a constraint on the development of a resource, as low quantities.

### 2.3.1. Geochemical studies

Advances in geochemical methods and approaches have aided our ability to interpret hydrochemical processes in groundwater systems, and improved understanding of how structural, geological, and hydrological features affect flow and chemistry (Glynn and Plummer, 2005). Multivariate statistical methods like cluster analysis classify and compare different chemical parameters of the water analysis and determines the relationship between them (Güler , et al., 2002; McNeil et al., 2005). The relationship of the statistically defined clusters of samples to geographic location illustrates an important message that geochemical survey datasets contain i.e. the variation in regional distribution.

Hydrochemical and isotope studies are frequently included in basement aquifer investigations and give valuable additional information on the structure of the aquifer system (i.e. McFarlane, 1992). In regional studies, hydrochemical and isotope data can be used to distinguish between shallow and deep aquifers (Nkotagu, 1996; Praamsa et al., 2009; Banks et al., 2009). They are also useful for identifying zones of interaction (mixing) and recharge processes (Sukhija et al., 2006; Jayasena et al., 2007; Horst et al., 2008). Radioisotopes such as tritium, $^{13}C$ and $^{14}C$ are used to determine the mean residence time (MRT) of groundwater. The accuracy of reliable dating of water is however often limited by the uncertainty surrounding the initial radioisotope concentration (Verhagen et al., 1991). More innovative and integrative methods for recharge characterisation and MRT are currently available such as chlorofluorocarbon (CFC) sampling. CFCs have provided useful tools for tracing and dating post-1945 water and groundwater mixing properties (i.e. Busenberg and Plummer, 2000; Gooddy et al., 2006; Horst et al., 2008).

## 2.4. Groundwater hydraulics

Crystalline basement aquifers can be considered to fall on a continuum between porous media and conduit systems (Cook, 2003). The unconsolidated weathered mantle can be represented by a porous medium, while the consolidated fractured bedrock can be regarded as a fractured porous media with groundwater flows in the conduit network and water stored in the aquifer matrix between the conduits. The analysis of pumping test data studies the behaviour of an aquifer inversely and suffers from non-uniqueness, where the observed response of an aquifer can be fitted with two or more sets of aquifer parameters, boundary and initial conditions that differ completely from one another (Van Tonder et al., 2001). Usually this is solved by assuming a simple model based on a set of hydraulic parameters, boundary and initial conditions of a known conceptual model. However, the difficulty is to identify the model that best represents reality.

### 2.4.1. Aquifer response evaluation

To circumvent the difficulty in choosing an appropriate conceptual model, diagnostic plots are constructed. Diagnostic plots include log-log plots of the drawdown versus the time, semi-log plots of drawdown versus time or drawdown versus distance to the well. The drawdown curve of the observed dataset is then compared to the characteristic type-curve of a known conceptual ('theoretical') model. Theoretical models comprise of 1) the type of aquifer (i.e. confined, unconfined or leaky), 2) inner boundary conditions associated with the pumped well (i.e. fully or partially penetrating, small or large diameter, well losses), and outer boundary conditions (i.e. constant head, impermeable walls, leaky or open conditions, or to extend to infinity). The classical theoretical diagnostic plots of the time-drawdown relationships of unconsolidated and consolidated aquifers can be found in Kruseman and De Ridder (1990).

The analysis of the logarithmic derivative to facilitate the identification of an appropriate conceptual model best suited to interpret the data became standard in the petroleum industry after the work of Bourdet et al. (1983). However, despite the early introduction of the concept in hydrogeology by Chow in the early 1950s the use of derivative analysis remains both under-used and under-reported in the hydrogeological literature (Samani et al., 2006). In South Africa, the use of derivatives to characterise drawdown behaviour is mainly due to the development of the Flow Characteristic Excel-programmed code by Van Tonder et al., (2001). The program provides powerful tools for the detailed diagnostic and analysis of step, constant and recovery drawdown data.

The modern techniques of model identification include the use of logarithmic derivatives together with the drawdown as a function of time in logarithmic scale. The main advantages and limitations of the use of both drawdown and its logarithmic derivative versus time in the hydrogeological field are discussed in Renard et al. (2009). In applying traditional techniques, it is not always easy to visualize whether the interpretation is valid or not. The derivative is highly sensitive to subtle variations in the shape of the drawdown curve, which makes the problems more visible. It is expected that with the automatic fitting techniques through commercial software (which offer derivative plots), that the use of the derivative for model identification will become common practice in groundwater supply investigations. Renard, (2005b) and Renard et al. (2009) provides an excellent synthesis of theoretical diagnostic plots (drawdown and derivative) from which the aquifer type can be inferred from, based on the drawdown behaviours in response to constant pumping rate (Figure 2.4). The classification relating to Figure 2.4 is: a) Theis model infinite two-dimensional confined aquifer; b) double porosity or unconfined aquifer; c) infinite linear no-flow boundary; d) infinite linear constant head boundary; e) leaky aquifer; f) well-bore storage and skin effect; g) infinite conductivity vertical fracture.; h) general radial flow—non-integer flow dimension smaller than 2; i) general radial flow model—non-integer flow dimension larger than 2; j) combined effect of well bore storage and infinite linear constant head boundary.

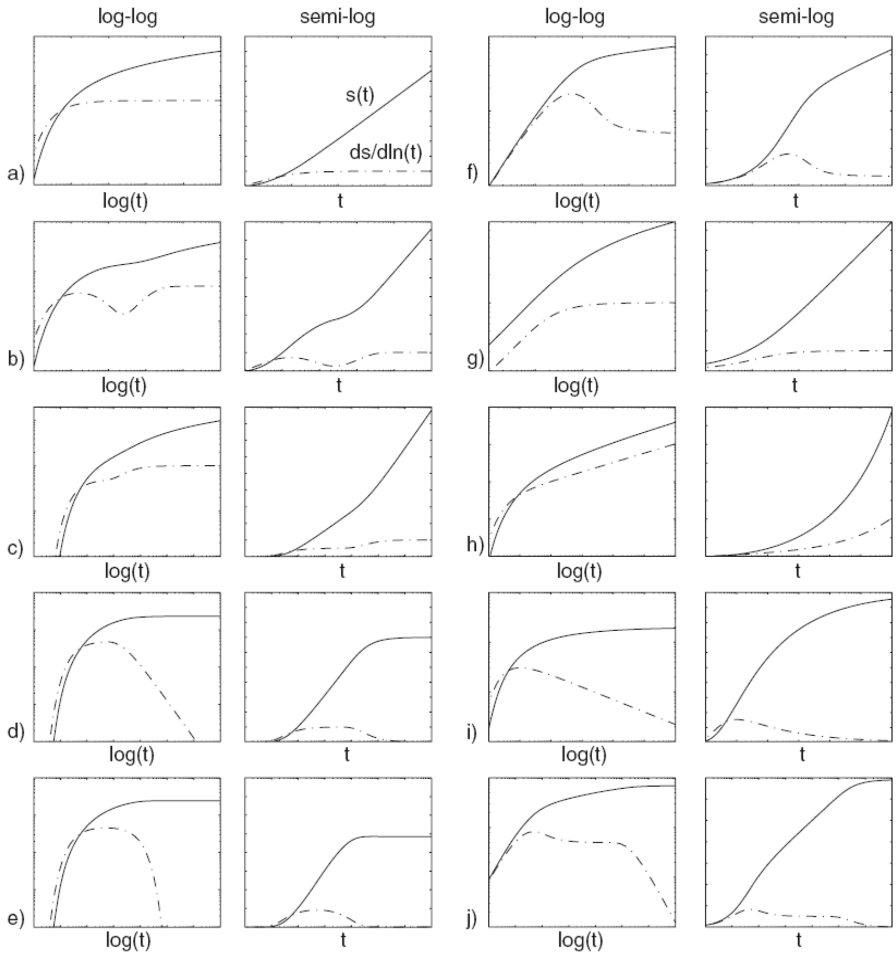


**Figure 2.4. Most typical diagnostic plots encountered in hydrogeology (Renard et al., 2009).**

### 2.4.2. Aquifer models applicable to crystalline basement aquifers

The history of well hydraulics and well testing started in 1863 with Dupuit, who developed the first analytical solution to model radial flow to a well in steady state. In 1935, Theis published the most important analytical solution. The Theis solution assumes that the aquifer is confined, bidimensional, homogeneous, and isotropic. A good synthesis of the historical and current perspective including the future of hydraulic testing is presented in papers published by Renard (2005a) and Butler (2008). Both of these authors have pointed out the concerns over the significance of results obtained from applying homogenous solutions to clearly heterogeneous aquifers. This was more vividly put by Wu et al. (2005) as: “Are we comparing apples to oranges?” Despite the inconsistencies and shortcomings identified by authors such as Wu et al. (2005) and Yeh and Lee (2007), traditional methods are still widely applied because they are able to solve the inverse problem and yield results. In addition, inferring the degree of heterogeneity from a pumping test is extremely difficult and solutions considering more complex aquifer situations with strong heterogeneity remain to be seen. Renard (2005a) and Butler (2008) concluded that conventional pumping test analysis will continue to play an important role in providing practical information in water supply investigations.

Since the early 1950s there has been a continuous and parallel development of analytical models and well-testing procedures that can be applied to weathered-fractured media such as: leakage from an adjacent aquifer (Hantush and Jacob 1955; Moench, 1985), partially penetrating well (Hantush, 1961), large diameter well (Papadopulos and Cooper, 1967), flow in an anisotropic unconfined aquifer with delayed gravity response (Neuman, 1974; Moench, 1997), dense network of fractures in a porous matrix (Moench, 1984; Barker, 1988), and single fracture intersecting the well (Gringarten et al., 1974; Gingarten and Ramey, 1974).

Many authors have indicated that crystalline basement rocks are usually semi-confined (fractured bedrock) with a water-table aquifer (the matrix - regolith) situated on top of it (Chilton and Smith-Carington, 1984; Rushton and Weller, 1985; Sekhar et al., 1994; Taylor and Howard, 2000; Van Tonder, 2002; Gonthier, 2009). These two components are hydraulically interconnected and cannot be treated separately. Consequently, many studies have applied a combination of pumping test solutions that govern vertical leakage such as the classical leaky-aquifer model or unconfined condition with delayed gravity response, while considering the double-porosity behaviour of the underlying bedrock (i.e. Taylor and Howard, 2000). To determine the existence of a vertical anisotropy of permeability in the fissured layer of a granitic hard-rock aquifer, Maréchal et al. (2004) interpreted the drawdown at the observation wells by means of the anisotropic unconfined Neuman (1972) method and at the pumping wells by using a horizontal fracture method developed by Gringarten and Ramey (1974). The study was further enhanced by applying the Barker (1988) theory, which takes into account the dimension of the flow, which results from the distribution and connectivity of the conductive fractures (Maréchal et al., 2007). Gernand and Heidtman (1997) conducted a 24-well 21 day pumping test to characterise a low-yielding fractured gneiss aquifer. Based on the drawdown curves, the authors used a single fracture model for this aquifer test, and showed that in low-porosity crystalline bedrock a single fracture zone may yield most of the water to a well.

### 2.4.3. Summary of conceptual models

To describe the heterogeneity associated with fractured aquifers, three main approaches are commonly used to model groundwater flow and solute transport namely 1) the equivalent porous media approach, ii) the discrete fracture network approach, and iii) the dual porosity approach (Figure 2.5). A practical guide of the advantages and limitations of each approach and the principles that guide the choice of modelling approach can be found in Cook (2003).

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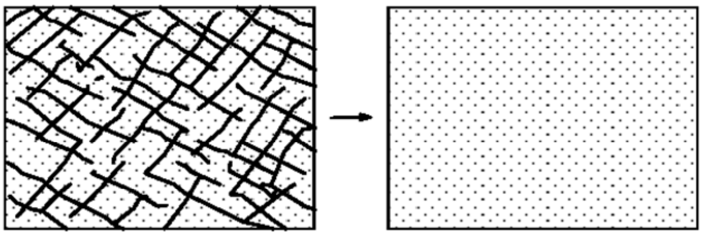
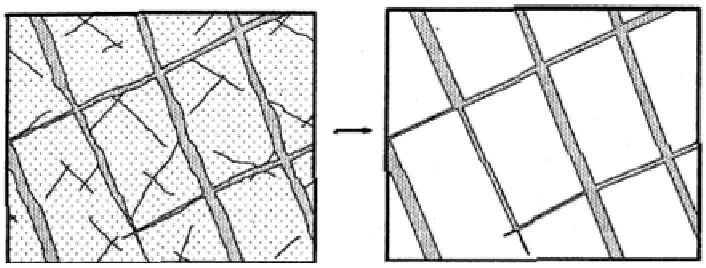
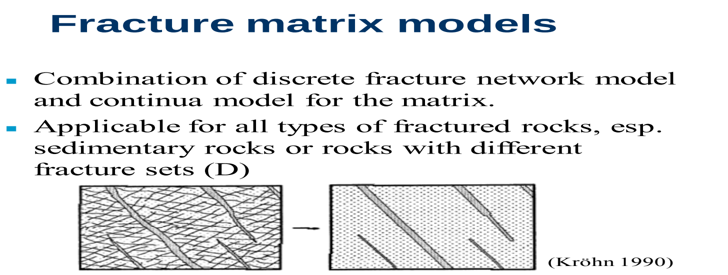
|  | **Equivalent porous media (EPM)**<br>• Hydraulic properties can be described with a representative elementary volume (REV) concept.<br>• Applicable foe homogenous, densely fractured rocks or matrix blocks |
|  | **Discrete fracture network models**<br>• Applicable for fractured rocks with impermeable matrix<br>• account for flow path geometry and fracture properties ( suited to smaller-scale modeling studies)<br>• Matrix diffusion and storage must be negligible |
|  | **Fracture matrix (dual porosity) models**<br>• Combination of discrete network model and continua for the matrix<br>• Applicable to most types of fractured rocks, especially sedimentary rocks<br>• Tendency to oversimplify geometry of the fracture network |

**Figure 2.5. Different modelling approaches for fractured rock aquifers (Kröhn, 1990).**

Modelling is important for improving our understanding of system behaviour. However, when constructing a conceptual model of a fractured rock aquifer, apart from identifying features that may be important in controlling the hydrogeology, it also depends on the scale of interest (Figure 2.6). A fractured rock aquifer may be connected on a large scale but may be dominated by a small number of larger fractures on a smaller scale.

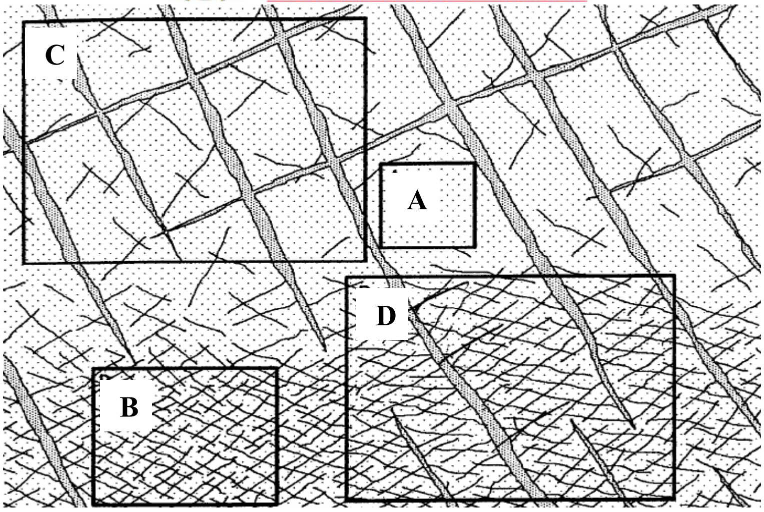



**Figure 2.6. Depending on the scale of interests a number of fracture flow models can be identified; matrix blocks (A), densely fractured rocks (B), fracture rocks with impermeable matrix (C), and combination of fracture network and matrix blocks (D) (Kröhn, 1990).**

It is clear that no single analytical method can be universally applied to crystalline basement aquifers when considering the analysis of pumping test data. Therefore, a summary of the concepts of the most applicable models is considered beneficial. Kruseman and de Ridder (1990) and Van Tonder et al. (2002) provide excellent well-illustrated handbooks to well-flow equations that cover a wider range of flow models and their application to field data.

*Homogeneously fractured, uniform aquifer (Ideal Confined)*

The aquifer is assumed to be infinite in lateral extent, fully confined (no recharge or leakage), two dimensional (large extension compared to its thickness), having a homogeneous transmissivity and storativity (Figure 2.7). In this approach, it is assumed that at the scale of interest the fractured aquifer behaves identically to an unconsolidated medium. A fractured aquifer will most likely fulfil this assumption if a dense network of uniform fractures intersects the rock. Theis (1935), and Cooper and Jacob (1946) described the unsteady-state radial convergent flow around the pumping well in a confined homogeneous and isotropic aquifer.

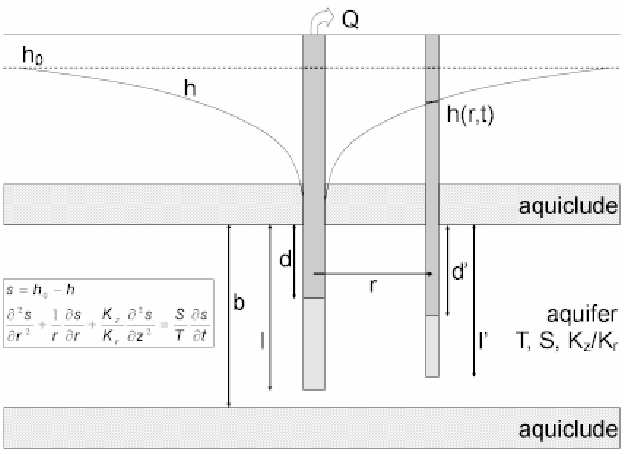



**Figure 2.7. Schematic illustration of an idealized confined aquifer.**

*Leakage through the confining layer*

This model considers a confined aquifer overlain by an aquitard and another aquifer (Figure 2.8). It is assumed that the pumped aquifer is recharged from the un-pumped aquifer through the aquitard. The pumped aquifer is an ideal homogeneous isotropic and infinite two-dimensional aquifer. The flow is assumed to be vertical in the aquitard, there is no storage in the aquitard, the head remains constant in the unpumped aquifer, and the flow remains horizontal in the aquifer. Hantush and Jacob (1955) developed the first analytical solution for this situation. Moench (1985) has included wellbore storage and wellbore skin, including three configurations for simulating a leaky confined aquifer with aquitard storage. Case 1 assumes constant-head source aquifers supply leakage across overlying and underlying aquitards. Case 2 replaces both constant-head boundaries in Case 1 with no-flow boundaries. Case 3 replaces the underlying constant-head boundary in Case 1 with a no-flow boundary.

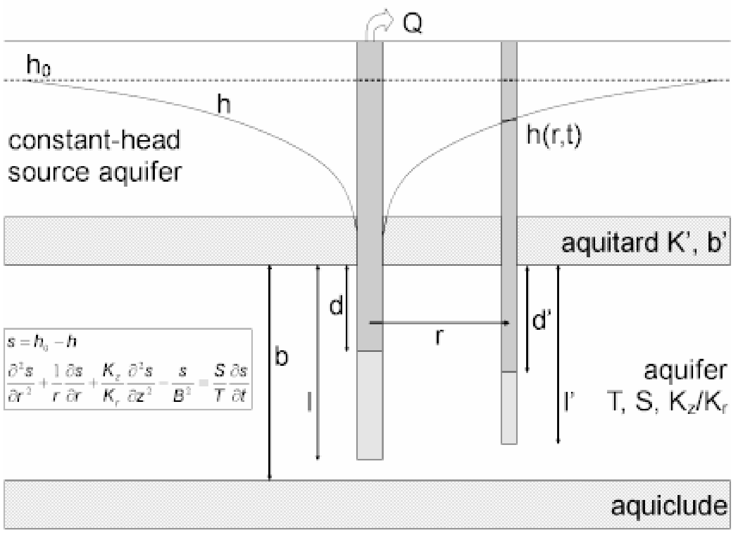



**Figure 2.8. Schematic illustration of an isotropic leaky confined aquifer.**

*Unconfined aquifer*

Unconfined aquifers are commonly encountered in well-test analysis and are also known as water-table aquifers. The aquifer is bounded below by an aquiclude, but is not restricted by any confining layer above it. Therefore the water table is free to rise and fall as the saturated zone is in direct hydraulic relation with the unsaturated zone. The approach most often used is based on the concept of a delayed water-table response. It was initiated by Boulton (1954) and developed by Neuman (1972, 1974). Time-drawdown curves on a log-log plot show a typical sigmoidal shape, with three distinct stages (Renard, 2005b). In the early time, the drawdown follows a Theis type curve corresponding to the release of water from elastic storage. Then, there is a transition with a flattening of the curve. For late time, the drawdown follows a second Theis curve corresponding to the release of water from the drainage of the unsaturated zone.

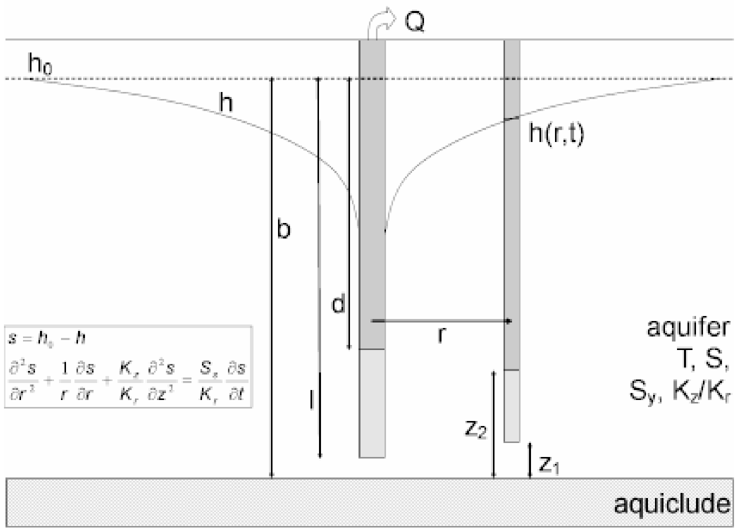



**Figure 2.9. Schematic illustration of an unconfined aquifer.**

*The double porosity model*

The concept of double porosity was introduced by Barenblatt et al. (1960), considering homogenous distributed conductive fractures embedded in a homogenous distributed matrix (blocks) (Figure 2.10). For both fracture and matrix, different conductivity and storage coefficients can be adopted (Van Tonder et al., 2002). The matrix blocks, however, are of low permeability but possess a high (primary) porosity and storage capacity. Only the fractures produce a flow directly to the well. The flow from the fracture into the well is radial. This implies a dense, homogeneous and continuous fracture network. The matrix blocks act as a source, which feeds water into the fractures.

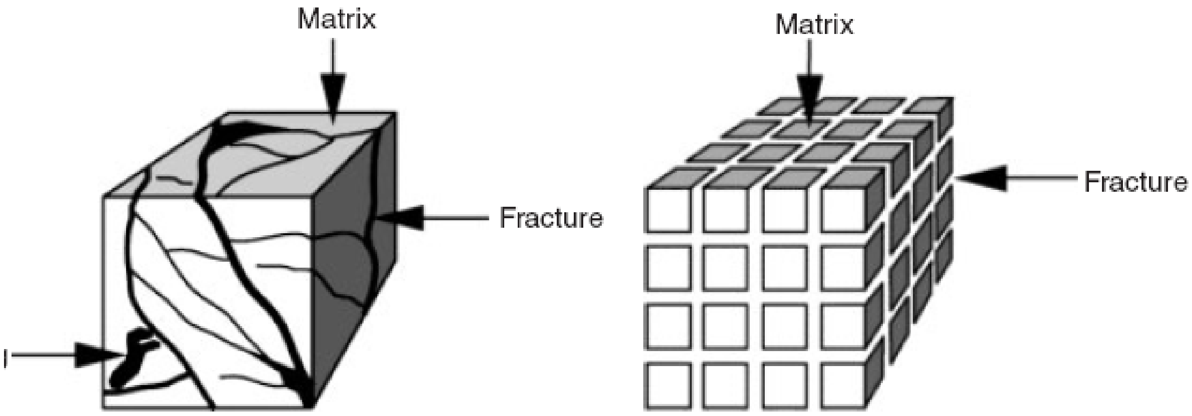



**Figure 2.10. A fractured block illustrating the double porosity concept (Cinco-Ley, 1996 in Renard, 2005b).**

Warren and Root (1963) introduced a pseudo-steady state block-to-fracture flow solution, but Kazemi (1969) using numerical models found that the flow is of transient block-to-fracture nature. Moench (1984) showed that the pseudo-steady flow case is, in fact, a special case of the transient flow restricted by a skin between fracture and matrix. Moench (1984) presented the most complete solution including pseudo-steady state and transient interporosity flow including wellbore storage, well skin and fracture skin, and is therefore more advanced than the simple straight line approach proposed by Warren and Root (1963). However, Moench (1984) assumed an infinite extent of the matrix and fracture system under confined conditions, including an aquifer with uniform thickness and matrix blocks that are slab shaped or spherical.

The typical sigmoidal shape time-drawdown curve observed is similar to that from an unconfined aquifer. During early time, the water is pumped from storage in the fractured system and the matrix does not affect the flow. At intermediate times, water is released from the matrix while the drawdown in the matrix is small compared to drawdown in the fractures. During late time, the drawdown in the matrix approaches the drawdown in the fractures and the aquifer behaves like a single porosity aquifer with the combined property of the matrix and the fractures.

*Individual fractures*

A more specific situation is the case of an individual fracture intersected by the well and acting as a drain in a larger porous aquifer. The concept assumes that a set of vertical fractures or a dyke can be idealised by a single vertical fracture which fully penetrates the confined and otherwise homogeneous aquifer (Bäumle, 2003). The unsteady-state flow towards the well follows distinct flow phases, which can be summarised as (Figure 2.11):

- Linear fracture flow (from fractures open to the borehole) is observed when the feature has a finite conductivity and is either embedded in an inert formation (matrix) or in a low conductive formation (Cinco and Samaniego, 1981).
- Bilinear flow occurs if the matrix is permeable enough; the linear flow in the fracture is superposed by a perpendicular linear flow from the formation to the fracture (where fractures are recharged via the pores).
- Linear flow from the formation to the fracture in the case of infinite conductive single features with negligible storage (Gringarten et al. 1974) (when all fractures have been dewatered and the rock mass determines the water supply to the borehole).
- Radial flow (also known as pseudo-radial flow or radial-acting flow) appears when the cone of depression is approximately circular. It is generally observed in a fully penetrating well (line source) located in homogeneous reservoirs, but also in a well in any fractured reservoir that can be considered as continuum. The start of the radial flow indicates the time at which the fractured reservoir behaves in a homogeneous manner.
- Spherical flow is observed in cases where the extraction source is a point in an isotropic medium, the cone of depression becomes a sphere (Gringarten and Ramey, 1973). In the real world, spherical flow will be observed only within small dimensions and over a short time period, because the spherical cone of depression will reach the bottom of the aquifer and the cone will become an ordinary radial flow.

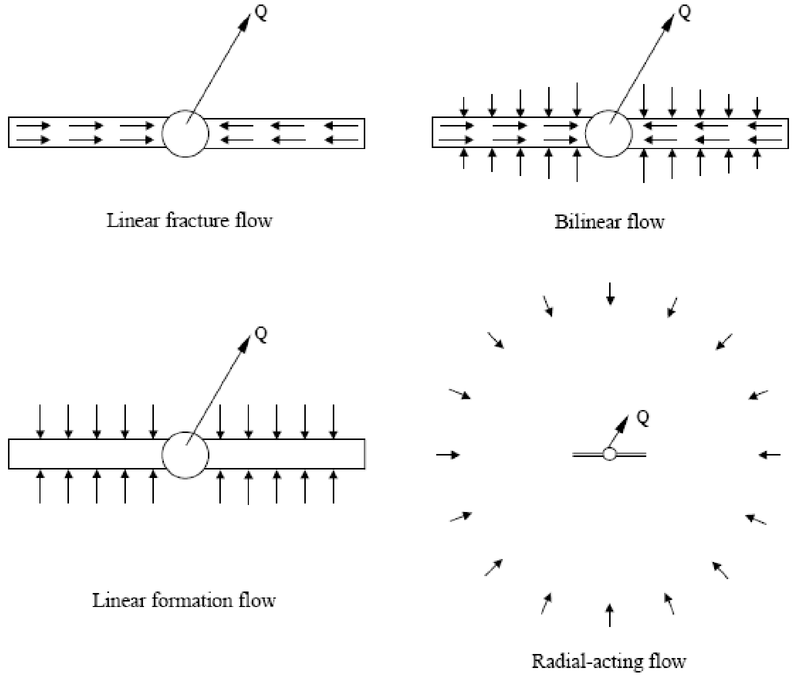



**Figure 2.11. Different flow phases observed in a single fracture (Van Tonder et al., 2002).**

Gringarten et al. (1974) developed an analytical solution to describe the unsteady-state linear flow from the rock formation into a well that fully penetrates a highly permeable vertical fracture zone. They considered a planar (zero-thickness) vertical fracture with negligible storage. It is assumed that the water is solely supplied by the host rock even at early times. They proposed two analytical solutions, which they referred to as the infinite conductivity, and the uniform flux solution. Their solutions are applicable if the fracture has very high or infinite conductivity. The advantage of the Gringarten type curve approach lies in the fact that only data of the transient phase from linear flow to radial-acting flow is needed (Van Tonder et al., 2002). In the case where the radial-acting flow starts data can be used for the estimation of the transmissivity, using common methods i.e. the Cooper-Jacob straight line method.

Gringarten and Ramey (1974) introduced an analytical model that describes the drawdown in a penny-shape bedding plane (horizontal) fracture with infinite conductivity and finite extension with uniform flux. The fracture is embedded in an infinite, homogeneous, horizontal matrix that has anisotropic radial and vertical conductivities and is limited by upper and lower impermeable boundaries. The model considers linear flow followed by radial-acting flow after a transition period.

*Generalised radial flow (GRF) model*

The spatial distribution of flow through the fractures towards the well depends entirely on the properties of the fracture network, such as fracture conductivity, fracture density and connectivity (i.e. Barker, 1988; Black, 1994). The characteristics of the fracture network determine the flow geometry, which is also known as the flow dimension. Addressing the concept of uncertain geometry of rock mass (i.e. porous or fractured dominance and preferred flow directions) requires the use of fractal dimensions (Black, 1994). The symmetry of flow dimension as described by Barker (1988) indicates that the relationship between cross-sectional area of flow and distance from the source is given by:

$$A(r) = \alpha_n r^{(n-1)} \quad (2\text{-}1)$$

where:

A(r) = cross-sectional area of flow ($L^2$)

r = radial distance from the borehole (L)

n = flow dimension (-)

The flow dimension n describes the geometry of the system by defining the rate that the cross-sectional flow area changes with respect to distance from the test borehole, i.e., the flow dimension is the power by which the flow area changes with respect to radial distance, plus one. Flow dimensions range between 1 and 3 (Barker, 1988; Black, 1994) and for a one dimensional flow geometry (n = 1), the area through which flow occurs will remain constant, regardless of the distance r (Figure 2.12).

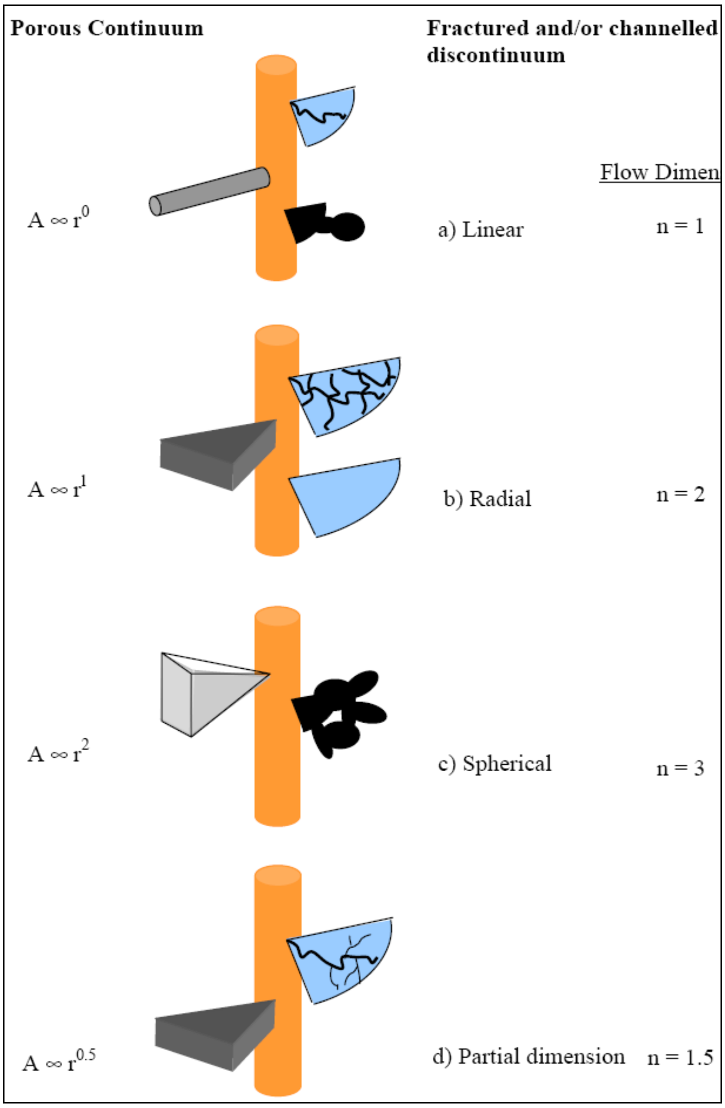



**Figure 2.12. Flow dimension definition in well testing (Doe, 1991 in Van Tonder et al., 2002).**

Flow towards a pumped well is usually concentrated along a certain fracture zone (one-dimensional) with large volumes of rock isolated from this zone of relatively high permeability activated by the pumping test. In contrast, the pattern of flow towards a fully penetrating well may be radial (two-dimensional) via a hard rock aquifer consisting of a well-connected fracture network isotropically distributed, or may be spherical (three-dimensional) if the well is only partially penetrating.

Barker (1988) introduced an analytical model that describes the drawdown in a fractured aquifer for various flow dimensions including linear, radial and spherical flows. These flow dimensions are seen as dependent on the fracture connectivity rather than as aquifer dimensions and are described by a factor n. Flow dimensions equal aquifer dimensions for integer values of n: for n = 1 the flow is strictly linear, for n = 2 the flow is radial (Theis model) and for n = 3 the flow is spherical. The source dimensions with a finite storage capacity are defined by $b^{n-3}$, where n = 1 implies a very thin cube source, n = 2 a cylinder source and n = 3 a sphere source, it extends as well to non-integer flow dimensions for intermediate cases (Figure 2.13). Matching of pumping test data with the GRF type curves (Barker, 1988) yields estimates of hydraulic diffusivity (i.e. the ratio of hydraulic conductivity and specific storage or transmissivity and storativity) and "generalized transmissivity".

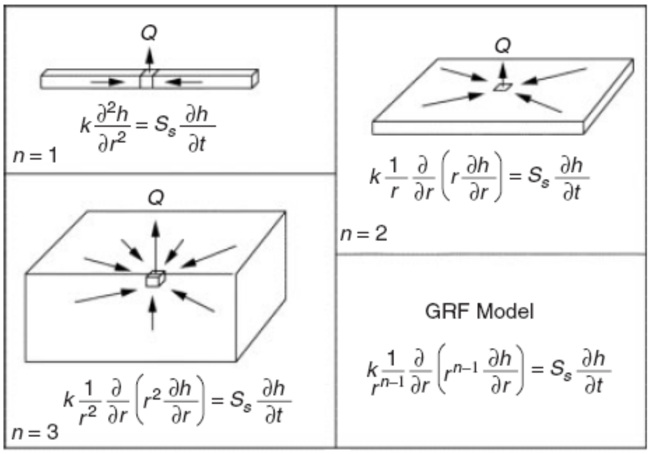



**Figure 2.13. Concept of radial flow in 1, 2, 3, and generalization to n dimensions (Renard, 2005b).**

## 2.5. 'Sustainable' yield concept

A misconception of the meaning of the word 'sustainable' in terms of groundwater use seems to exist, leading to degradation of wetland and riparian ecosystems due to stream dewatering and groundwater depletion. Sustainable yield is often confused with 'safe yield', which assumes the attainment of a long-term balance between groundwater abstractions and annual recharge and often calculated as a percentage of the natural recharge (Sophocleous, 1997; Zhou, 2009). The concept of 'sustainable' yield was introduced to overcome the shortcomings of the safe yield idea. In simple terms groundwater sustainability can be defined as development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley et al., 1999).

Despite Bredehoeft's (2002) provocative theory, known as the "water budget myth", that sustainable groundwater development has almost nothing to do with natural recharge, it is still widely accepted that natural recharge is a very important factor in the assessment of sustainability (Sophocleous, 2005; Alley and Leake, 2004; Kalf and Wooley, 2005, Zhou, 2009). However, Bredehoeft (2002) reminded hydrogeologists that aquifers are more complex than an oversimplified water balance can accommodate. According to Devlin and Sophocleous, (2005) distinction should be made between the concepts of sustainable pumping rate (source yield) and sustainability (resource yield) and that recharge rates cannot be ignored in spite of the fact that sustainable pumping rates can be estimated without them.

*Resource yield*

Aquifers are in a state of natural long-term equilibrium prior to pumping, and in order to maintain this equilibrium, groundwater abstractions must be balanced by increased recharge (increase in the amount of water entering the system) or reduced discharge (reducing the amount of water leaving the system) (Figure 2.14). The increase in recharge and decrease in discharge is termed 'capture' and equilibrium is achieved when it balances pumping. Thus, it is only after pumping that the change in recharge will contribute to the determination of a sustainable yield (Seward et al., 2006). When considering a groundwater basin as whole, all the individual abstraction points where 'capture' is possible, permissible and sustainable, will together define the basin yield (Seward et al., 2006).

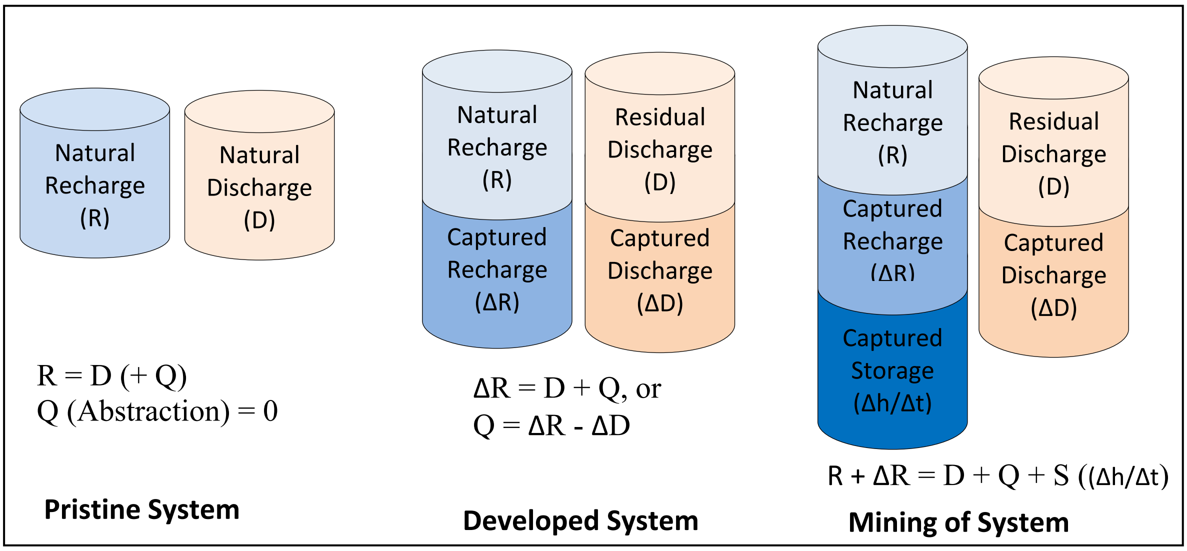



**Figure 2.14. The capture principle and the implications for sustainability and recharge.**

Abstractions from storage indicate on the other hand non-equilibrium conditions. Where the abstraction is greater than the difference between the maximum inflow (R+ΔR) and residual outflow (D) then an additional mining yield (change in S) is required to maintain the abstraction rate (Figure 2.14). It must be emphasized that the spatial distribution of these abstraction points strongly influences the total sustainable basin yield. Withdrawals from an aquifer might have a severe impact on individual ecosystems locally, but per square kilometre these withdrawals might be minor in terms of total recharge and discharge. Hence, a sustainable yield should account for small-scale local impacts and simultaneously consider the ability of an aquifer as a whole to recover from pumping stress (Maimone, 2004).

Many may argue that the "capture recharge principal" does not generally apply to basement aquifers as the resource yield is rarely achieved due to poor boreholes yields and low distribution densities. However, despite the relatively low (often less than 1 ℓ/s) borehole yields in the Limpopo crystalline aquifers, deeply weathered and highly fractured regions boreholes can have yields in excess of 5 ℓ/s. A number of exceptionally high yielding areas not known anywhere else in Africa within the basement aquifer system occur in the Dendron (Mogwadi), Baltimore and Tolwe regions (Figure 1.1). These aquifers have sustained (supposedly sustainable) large scale irrigation for the last few decades, suggesting high storage potential, high permeabilities and an interconnected fracture network with a major source of recharge. Seeing that abstraction rates far exceed vertical recharge rates which amounts to a few millimetre of the 400 mm annual rainfall, it can be argued that these aquifers are potentially recharged through lateral saturated flow from adjacent aquifers, sometime called inter-aquifer recharge.

*Source yield (Sustainable pumping rate)*

If several hydrogeologists were asked how they arrive at their recommended borehole yield, the answers would be vague. Many of them would place the emphasis on experience in analysing the shape of the pumping test curve for multiple discharge tests (step test), constant discharge tests and recovery tests. In reality only through long term monitoring and groundwater flow models can a long term 'sustainable' pumping rate be determined. However, in many rural water supply projects it is simply not economical to study each aquifer in detail to ensure that the boreholes will not fail. In South Africa its common practice to try and maintain operational pumping levels above the level of the main yielding fracture. The sustainable pumping rate is in this context defined as the discharge rate that will not cause the water level in the well to drop below a prescribed limit, identified from the nature and thickness of the aquifer (especially water strikes) and the depth of the well. Van Tonder et al. (2001) compiled a user-friendly Excel spreadsheet known as the Flow Characteristic-method to recommend long term pumping rates for water supply boreholes in fractured rock. The FC-spreadsheet addresses the long-term assurance of water supply from a borehole based on available drawdown figures and estimates the influence that boundaries may have on the yield of a borehole. A complete explanation of the semi-analytical expressions and approximations can be found in a *Journal of Hydrology* publication by Van Tonder et al., 2001. The recommended 'sustainable' yield ($Q_{sus}$) is determined as:

$$Q_{sus} = Q_{ob} \frac{S_p}{S_{ob}(t')} \qquad (2\text{-}2)$$

where $S_p$ is the drawdown of the well corresponding to the prescribed limit, $S_{ob}(t')$ is the observed drawdown at the time t′ during a test with a constant discharge rate $Q_{ob}$ and t′ represents the minimum operation time in which the drawdown shall not exceed the prescribed limit. In order to estimate the sustainable yield, $S_{ob}(t')$ needs to be known over a long time period. $S_{ob}(t')$ is generally extrapolated using Theis's well equation or a Taylor series expansion based on the extrapolation of drawdown measurements at late time, including drawdown derivatives.

Although it is widely used in practice and has been adopted by Department of Water Affairs, the FC-spreadsheet is often misinterpreted and its limitations are not taken into account by the user, which include:

- The determined 'recommended' yield estimate is based on a probability of not exceeding the available drawdown. Such an approach does not follow the original sustainability concept (Alley et al., 1999), which takes environmental and social issues as well as the long-term protection of resource into account.
- The determined yield might be non-unique and dependent on the abstraction rate during the constant rate test and the extrapolation of the measured drawdown.
- If there are more than one abstraction boreholes in the aquifer system, the sum of the 'sustainable' yields must not be higher than the annual recharge for the area.

### 2.6. Development of groundwater

Studies on crystalline basement aquifers have predominantly focused on the development of groundwater resources in thick regolith (i.e. weathered overburden) with dominant intergranular flow in mainly tropical to sub-tropical regions (i.e. western and southern Africa and South America) (Wright and Burgess, 1992). Early workers focused mainly on establishing a correlation between the yield of a borehole and 1) its depth, 2) the geology, and 3) weathering thickness (i.e. Houston and Lewis, 1988; Barker et al., 1992; McFarlane et al. 1992; Chilton and Foster, 1995).

More recently, researchers have tried to identify the most important factor(s) in controlling borehole yields in crystalline terrain, in order to identify areas with higher groundwater potential (Mabee, 1999; Moore, 2002; Henriksen, 2003; Neves and Morales 2007). The influence of topography on borehole yield have been shown by many (i.e. McFarlane et al. 1992; Mabee, 1999; Henriksen, 1995) with the common result that wells located in valleys and flat areas show generally higher yields compared to wells located on slopes and hilltops. Although, specific rock types (i.e. granites, gneiss, schist) are in many cases the obvious factor in explaining the variation of borehole yields (Gustafsson and Krásný, 1994; Neves and Morales 2007), the influence is often supplanted by secondary features such as faults, fracture zones and dykes. As a result throughout the last decade the optimization of the location of wells in tectonically fractured areas throughout Africa, India and Brazil focused mainly on assessing the relationship between bedrock structure and groundwater production by analysing the position of wells in relation to lineaments (aeromagnetic data or Landsat images) (i.e. Greenbaum 1992; Fernandes and Rudolph, 2001; Owen et al., 2007; Solomon and Quiel, 2006; Henriksen and Braathen ,2006; Ranganai and Ebinger, 2008; Solomon and Ghebreab, 2008). These investigations are often based on tectonic models where the impact of original or present compressional stress on potential water bearing lineaments is assessed (Fernandes and Rudolph, 2001; Henriksen and Braathen, 2006; Neves and Morales, 2007; Owen et al., 2007). In some cases results showed that the majority of productive water wells are associated with lineaments parallel to the regional maximum horizontal stress in the area (Fernandes and Rudolph, 2001). It is therefore expected that fractures perpendicular to the regional compressive stress are closed and dry (Owen et al. 2007). However, in many cases authors could not establish a firm relationship between well yields and lineaments (Greenbaum 1992; Gustafsson, 1994) and in most cases, there is no direct evidence that the structures responsible for the flow correlate with mapped lineaments (Mabee et al., 2002). According to Sander (2007) this may be attributed to local factors such as fracture infilling, fracture connectivity or the poor knowledge of current stress regimes. It is recognized that lineament mapping is often subjective (Mabee et al., 1994) and depends on factors such as data quality, extraction technique and interpretation method. But when correctly interpreted lineaments are used in conjunction with a good understanding of local geology, tectonics, geomorphology, hydrology and aquifer characteristics, the most promising setting and orientation of fractures for future groundwater exploration can be identified (i.e. Solomon and Quiel, 2006; Galanos and Rokos, 2006; Ranganai and Ebinger, 2008; Solomon and Ghebreab, 2008).

### 2.6.1. Exploration approaches

Due to the complexity of the geology, poor groundwater recharge and for many regions inadequate geological and geomorphology maps, the location of groundwater in crystalline bedrock will always be difficult. Although, groundwater is available for all rural communities as low yielding hand pump boreholes, it is only by detailed groundwater investigations and exploration that successful high yielding well fields may be developed. Sami (2009) placed special emphasis on a comprehensive geodynamic / strain analysis, highlighting the structural control of groundwater flow in the fractured aquifer (Figure 2.15). However, the approach overlooks the importance of geomorphologic processes on the nature and extent of weathering. In reality various groundwater exploration programmes may be followed. Some projects focus largely on lineament mapping (GIS & remote sensing), some projects have a strong focus on structural and tectonic history (i.e. Sami, 2009), while other projects follow a strong geophysical approach (Sander, 2007). In this regard the application of good base work in terms of aquifer characterisation before drilling commences is often overlooked.

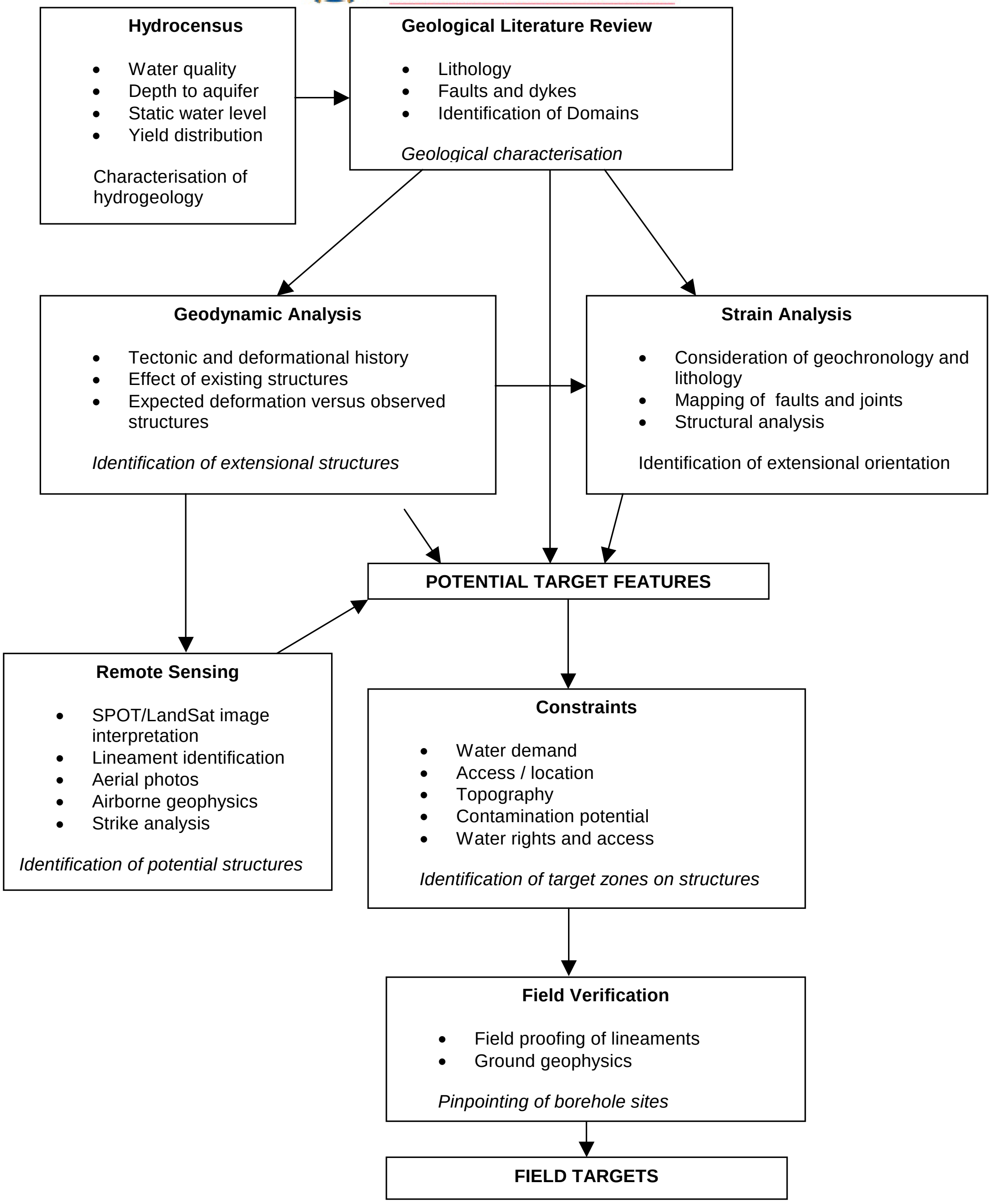



**Figure 2.15. Flow chart of recommended groundwater exploration of basement aquifers (Sami, 2009).**